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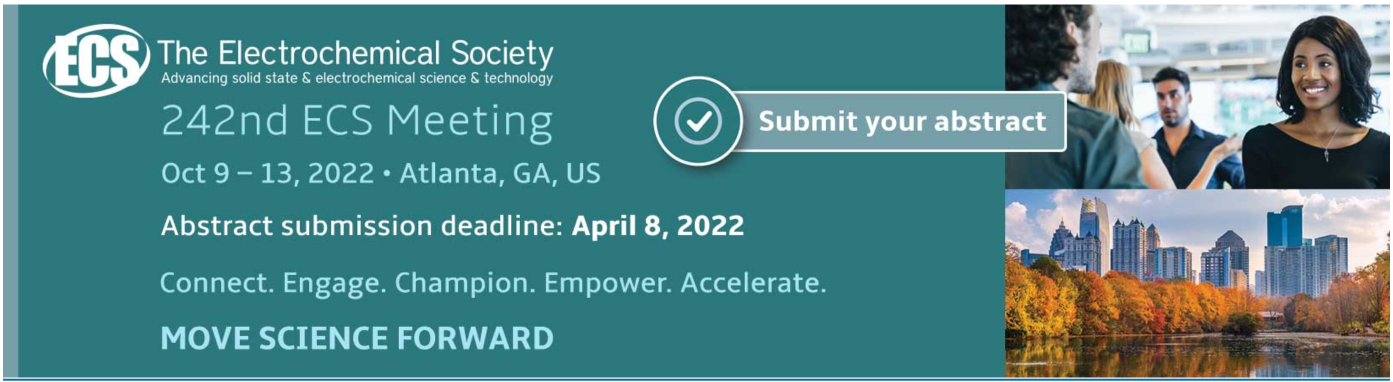

Analysis of the application of fuselage skin reinforcements with beam element representations in flexible full aircraft models for ditching simulations

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Abstract. The aim of this paper is the application of beam element representations for structural skin reinforcements in flexible full aircraft FE models used in ditching simulations. To verify this approach, it was initially analyzed on flexible reinforced bottom-aircraft panels under guided ditching conditions, considering also structural mesh size variations and partly corresponding fluid mesh densities. For this analysis two different numerical methods were used for comparisons, the coupled Finite Element-Smoothed Particle Hydrodynamics and the Arbitrary Lagrangian Eulerian methods. For the generation of the full aircraft model a multidisciplinary process chain approach and a standardized data format description are used. The beam element representations are considered for the modelling of skin reinforcement as well as other structures like cabin and cargo floor structures. By this approach, first time feasible full aircraft ditching simulations and the subsequent analysis of both global kinematics and the local fuselage structural response could be achieved.

1. Introduction

Novel aircraft designs must be compliant to crashworthiness certification requirements. One requirement is to investigate the behavior of the aircraft exposed to the hydrodynamic loads expected in a planned emergency landing on the water, commonly known as ditching. Contrary to a crash on water which can be described as an unexpected and unprepared event, ditching is characterized by the level of preparation prior to the impact. Low approach speeds, a nose-up position of the aircraft, the consideration of the sea state and the direction of the wind as well as the cabin preparation are pursued by the pilots and the crew in order to reduce the impact loads and deaccelerations to increase the survivability of the occupants and their subsequent evacuation [1]. Diverse methods can be applied by aircraft manufacturers to demonstrate compliance with respect to ditching requirements. Nevertheless, computational numerical approaches in combination with detailed aircraft models allow not only for the analysis of the global kinematics of the aircraft, but also for the investigation of the local airframe structural integrity. This work focuses on the impact phase, where the highest hydrodynamic loads are present and the subsequent landing phase, characterized by different hydrodynamic phenomena induced by the high forward velocity and the specific shape of the rear bottom section of the aircraft.

The generic character of this investigation is adopted by the application of a tool used in multidisciplinary aircraft pre-design process chains for the description of an aircraft configuration and the generation of the detailed flexible aircraft models. In combination with the development of suitable modelling methods for the structure and the fluid, this kind of aircraft models can be used in ditching simulations. Initial investigations on the application of beam element representations replacing typical extruded shell element structures, such as for skin reinforcements in flexible aircraft panel models, showed advantages in terms of computational effort with qualitatively very similar structural behavior [2]. The transfer of this modelling technique to a much coarser full aircraft model for affordable ditching computations is a main objective of this work.

In the first part of this paper two numerical approaches applied to model the transient interaction of fluid and structure are presented. The next part includes the description of the modelling technique and of the test cases with flexible aircraft panel models, followed by the verification in a guided ditching condition using different numerical approaches to extend results presented in [2]. The transfer of the modelling technique to a flexible full aircraft model for the application in ditching simulations is presented in the next section. Finally, conclusions of this work are given.

2. Numerical approaches

The numerical simulation of a water impact is challenging, as it is considered as a multi-model coupled-approach where considerable fluid displacements and a nonlinear response of the structure is expected due to the high hydrodynamic loads. In order to attempt for an efficient and affordable computation, the fluid and the structure are discretized with different suitable numerical approaches and computed using an explicit time integration scheme. In this work the Finite Element (FE) method and a Lagrangian formulation is used to discretize the structural sub-model and compute the deformation of the material and the mesh. This method is common for structural models in crashworthiness calculations.

The fluid sub-model is treated differently compared to the structural model. In this work two different approaches are considered. One method commonly used for this type of application is the Smoothed Particle Hydrodynamics (SPH), a Lagrangian mesh-free method in which the continuous fluid domain is discretized by a set of particles which moves with the flow. The condition at each particle position is then estimated as a weighted average of the properties of the neighboring particles [3]. Since large water basins are commonly used in ditching simulations, computational effort and boundary effects can be reduced using a hybrid modelling approach by introducing a portion of the fluid domain discretized with FE brick elements surrounding the SPH domain which are coupled to the particles using a node-to-surface penalty contact formulation [4].

Another approach used widely for fluid dynamics computations is the Eulerian formulation. Contrary to the Lagrangian method where the mesh moves with the material, in the Eulerian approach the mesh remains fixed while the material moves through the fixed mesh, thus being appropriate for models presenting large material deformations. In addition, in the Arbitrary Lagrangian-Eulerian (ALE) method the mesh motion is arbitrary with respect to a fixed special frame, thus combining the advantages of using the Lagrangian method for the structure and the Eulerian method for the fluid [5]. Both sub-models are then coupled using an embedded contact interface with the structure immerged in the fluid domain. This Coupled Euler-Lagrange (CEL) method is the second approach used in this work.

3. Modelling techniques of beam-stiffened aircraft structural models for ditching simulations

The first model considered in this work is a beam-stiffened flexible aircraft fuselage panel used for guided ditching simulations. This model was developed starting from a generic detailed lower fuselage panel with individually modelled skin, stringers, frames, and local clips, including connections via individual joints and tied interfaces [6]. This reference panel was simplified with skin and reinforcements modelled using a conformal mesh with common nodes at the intersections of stringers and frames to reduce model complexity for an easier conversion between used codes (Simplified shell-stiffened aircraft panel, in Figure 1). In the final model development step, representative beam elements were integrated to model the stringers and inner frames (Beam-stiffened aircraft panel, in Figure 1), instead of the previous extruded representations with shell elements [2]. The material here is an aluminum alloy AL2024 with density 2.8 x 10^{-6} kg.mm^{-3}, Young modulus 72.14 GPa, Poisson ratio 0.33, and initial yield stress 0.3268 GPa. The isotropic hardening of the material is modelled using a tabulated plasticity curve, as presented in [2]. Panel length, width, and curvature are 1127 mm, 795 mm, and 2000 mm, respectively. The skin thickness is 0.8 mm and the standard mesh size is 10 mm. Stiffeners dimensions are reported in [2]. Figure 1 portraits the aircraft panel model in the different development stages mentioned above.

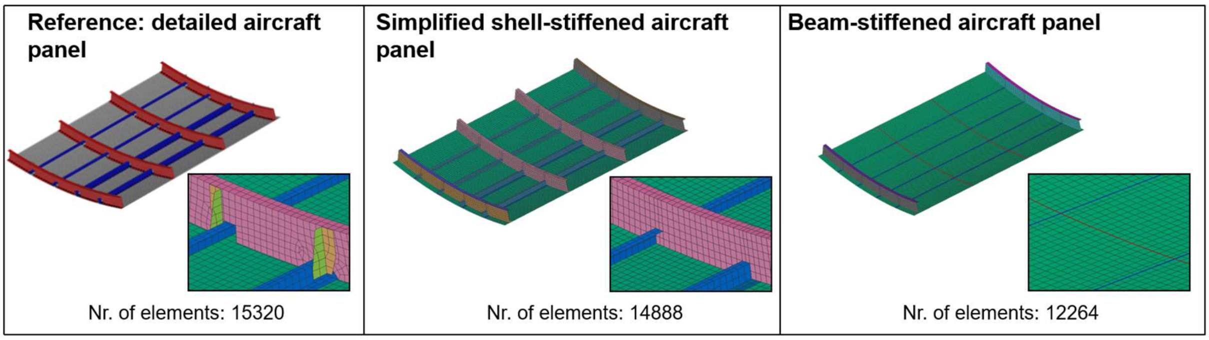

Figure 1. Generic detailed aircraft panel (Left), simplified shell-stiffened panel (Center), and panel with integrated representative beam FE in skin reinforcements (Right).

In addition to the integration of beam elements, different mesh sizes were considered to analyze their implication toward the full-aircraft application. As reported in [2], computations with the beam-stiffened aircraft panel using the coupled SPH-FE method already showed comparable results with a coarser mesh size of 20 mm (3398 elements in total). The computational effort in terms of elapsed time could be considerably reduced in combination with corresponding coarser fluid domains. In this section additional results of the beam-stiffened aircraft panel ditching computations using the ALE-CEL method are presented.

3.1. Reinforcements modelling

Results of the guided ditching simulations using the reinforced aircraft panel with integrated beam element representations for the inner frames and stringers are presented for both ALE-CEL and SPH-FE methods in Figure 2. The contour plot presented on the left side shows the pressure fields in the fluid at 50 ms, during the contact of the forward bay section with the water surface. While ALE calculates a comparably smooth pressure field in the fluid, the SPH method leads to an irregular pressure field. However, the flow front in the SPH-FE calculation (bottom) appears to be very similar to the one in the ALE-CEL computation and in both simulations the highest pressures are found in the area behind the water front. The time history of the vertical force in global z direction (Figure 2, right) reveals in general slightly higher forces calculated with the ALE-CEL method. The comparison between the considered structural models however shows a good agreement for both methods, especially between the simplified panel with extruded reinforcements modelled with shell elements and the beam-stiffened model. In both computational methods (ALE-CEL and SPH-FE), the shape of the curves and the maximal force levels are very similar to the results with the reference model.

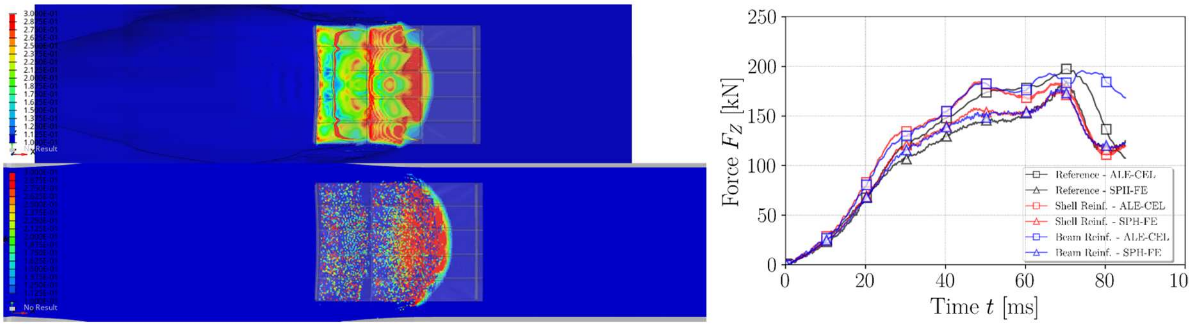

Figure 2. Guided ditching simulation with the beam-stiffened fuselage panel at 50 ms for both considered computational methods. Left: Contour plot of the fluid pressure in MPa, ranging from 0.1 MPa to 0.3 MPa (Top: ALE-CEL. Bottom: SPH-FE). Right: time history of the vertical force.

3.2. Mesh size variation

Figure 3 shows results of the guided ditching simulation with the beam-stiffened panel considering a coarser structural mesh size and an unchanged fluid representation. The contour plot on the left side of Figure 3 denotes a very similar interaction between the fluid and the structure compared to the results presented in Figure 2 with the standard mesh size. The response of the structure is very similar to the previous calculation and a very good agreement compared to the reference panel is found for both computational methods, according to the vertical force time history (Figure 3, right).

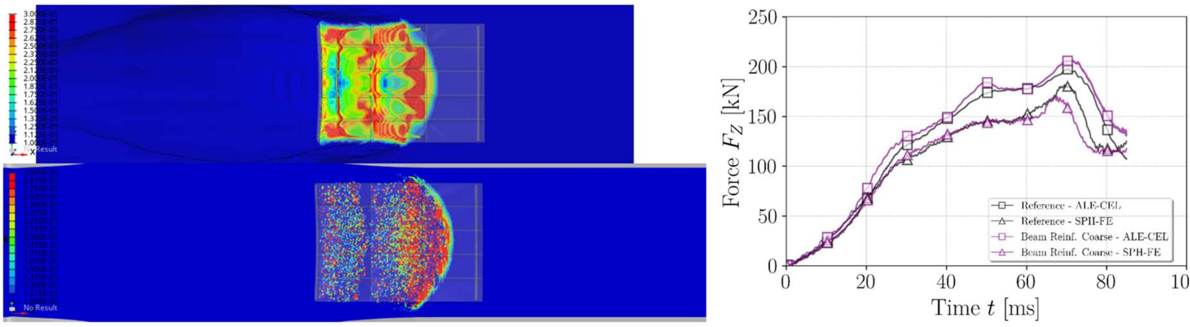

Figure 3. Guided ditching simulations with the beam-stiffened fuselage panel including a coarser mesh size at 50 ms for both computational methods. Left: Contour plot of the fluid pressure in MPa, ranging from 0.1 MPa to 0.3 MPa (Top: ALE-CEL. Bottom: SPH-FE). Right: time history of the vertical force.

The force obtained with the ALE-CEL method is still slightly higher compared to the result obtained with the coupled SPH-FE approach. An investigation into the local responses of the beam-stiffened panel in guided ditching conditions (standard and coarser mesh size) is presented in Figure 4. Results show higher relative vertical displacements for computations with ALE-CEL in both cases, independent from the structural mesh sizes. This is consistent with the forces comparison. Apart from little method specific aspects, the behavior of the beam reinforced panel with both methods is comparable and the coarser mesh decreases significantly computational costs.

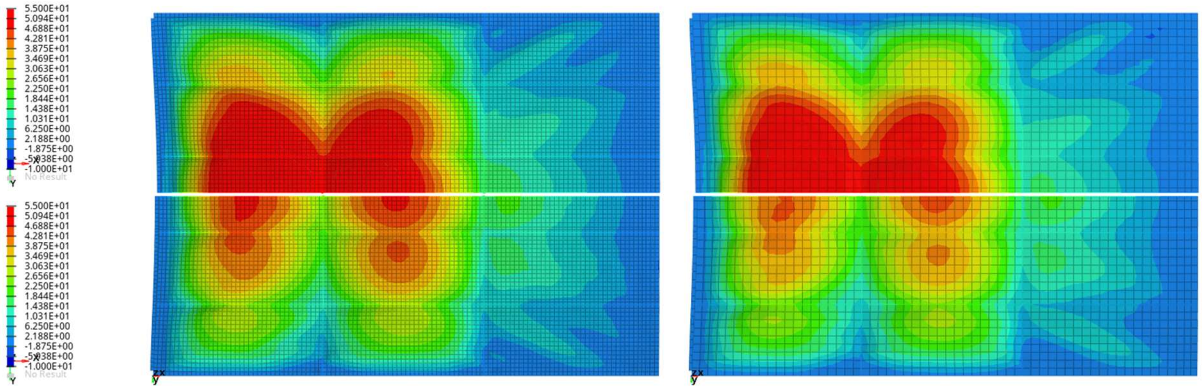

Figure 4. Contour plot of the relative vertical displacement of the beam-stiffened fuselage panel at 50 ms for both considered computational methods. Top: ALE-CEL, Bottom: SPH-FE. Left: standard mesh size. Right: coarser mesh size. Visualization of the LH or RH panel-half in flight direction, respectively.

3.3. *Fluid particle density variation*

Further computations with the beam-stiffened aircraft panel and the coarser mesh size are performed with a coarser fluid particle density for the coupled SPH-FE method. Results are presented in Figure 5. The time history of the vertical force indicates a higher prediction of the force with the coarser fluid density, compared to the reference panel and the computation with a standard water domain. However, the shape and the maximal force levels are comparable.

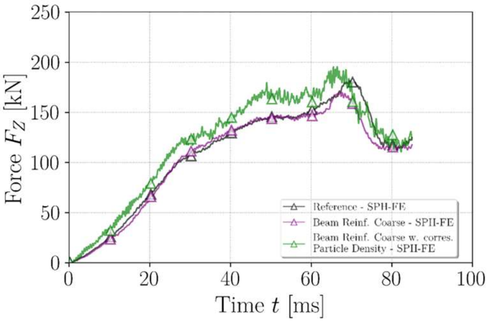

Figure 5. Time history of the vertical force obtained for the beam-stiffened aircraft panel model with a coarser mesh size and a corresponding coarser fluid particle density.

With respect to the computational cost, the use of the coarser fluid particle density in combination with the beam-stiffened aircraft panel and the coarser structural mesh leads to a reduction of a factor 15 of the computational effort compared with the standard model. The reduction of the elapse time is therefore very attractive for the full-aircraft ditching simulation.

4. Modelling technique transfer to a flexible full-aircraft model for ditching simulations

The integration of representative beam FE for the discretization of fuselage skin reinforcements in a full flexible fuselage model is assessed in this section. The general description of the aircraft system as well as the generation of the structural FE model of the full-aircraft is reached using a multi-disciplinary approach and a tool for structural analysis. For the pre-processing and modelling of the water domain and the coupling, several python-based routines were used.

4.1. Model generation

The aircraft considered in this work is the 'DLR D150' generic aircraft. This aircraft is similar to a commercial fixed-wing single-aisle aircraft used for short to mid-range missions with a capacity of 150 passengers. The design of this aircraft is based on a multi-disciplinary process chain considering inputs from specific tools for outer geometry, cabin design, aerodynamics, structure, powerplants, etc. For the description of the aircraft design the hierarchical XML-based data format called CPACS (Common Parametric Aircraft Configuration Schema) was used [7]. This data format provides the basis for the python-based modelling and sizing tool PANDORA (Parametric Numerical Design and Optimization Routines for Aircraft) [8], which was used for the generation of the flexible FE fuselage model of the D150 aircraft. To generate the reinforced fuselage skin, the tool reads the CPACS-inputs of the fuselage geometry, reinforcement positions, and structural profiles description including the cross-section. This cross-section is used by the tool to determine engineering constants used as inputs for the beam elements. According to the positions of the reinforcements, beam finite elements are created by the tool. Beside stringers and frames, PAX and cargo floor structure are represented with beam elements, too. Finally, additional structural components such as bulkheads and the center wingbox are modelled automatically. The elastic-plastic material model of the AL2024 described above is used for the fuselage. Figure 6 shows the fuselage of the D150 FE model. The outer skin panels, modelled using shells, are hidden here for visualization purposes.

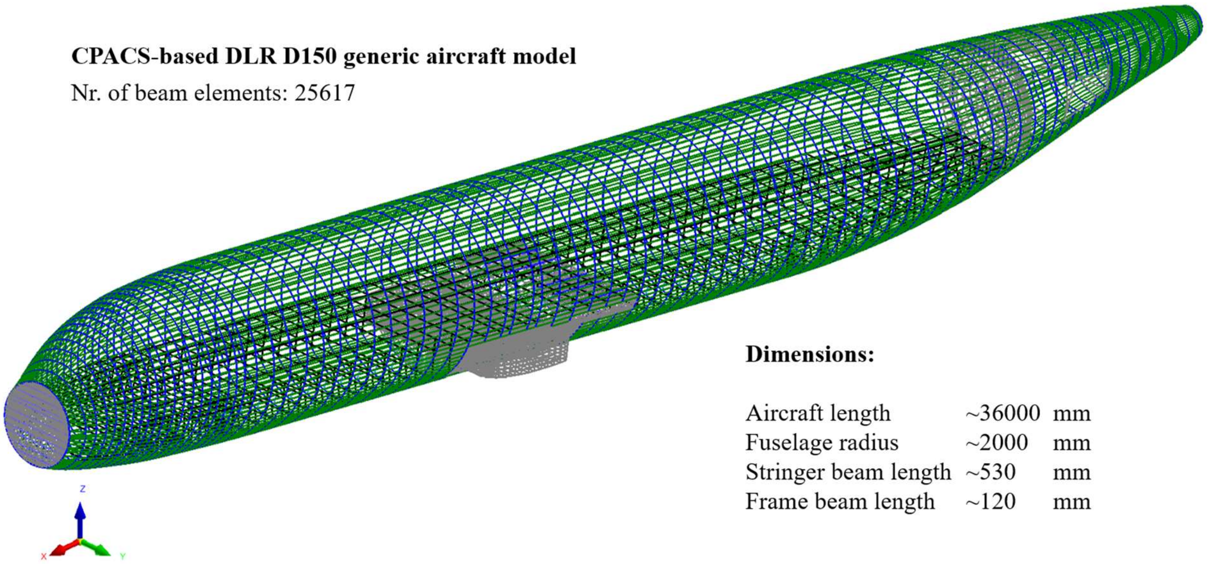

Figure 6. Generic fuselage structural model with beam FE representations for fuselage skin and panel reinforcements. The configuration is a short to mid-range single-aisle aircraft model.

4.2. Global FE full-aircraft model ditching simulation

A fixed-wing twin-engine GFEM aircraft model including the flexible fuselage model depicted in Figure 6 is used for ditching simulations in free motion conditions. The wings, the empennage and the engines are modelled with rigid bodies and are coupled to the flexible fuselage. Pylons are modelled with 1D elements to connect the engines to the wing. Since the interaction between the engines and the water influences the kinematic behavior of the aircraft, connections between the pylons and the engines can fail when reaching a critical load to allow a more realistic ditching scenario. Global aircraft mass properties are reached by integration of over 1500 lumped masses for payload and secondary masses, which are coupled to the structural mesh with the use of interpolation elements.

The approach configuration of the aircraft, prior to the impact on water, is symmetric with a sink rate of 1.5 m.s^{-1}, a forward velocity of 70 m.s^{-1}, and a pitch angle of 8°. In total, the ditching simulation runs over 2000 ms, which covers the impact and a significant part of the landing phase. Computational results are obtained using the coupled SPH-FE approach. The length, width and depth of the water basin are 200 m, 24 m and 2 m, respectively. In total 1.2 million SPH particles, with a particle spacing of 0.2 m, equivalent to a total volume of 9.6 million liters are used in the computation. In this first simulation a simple lift model with a linear decrease was used. The lift force balances the aircraft weight at the beginning of the computation and is zero 2000 ms after the impact. The interaction between the flexible aircraft and the water domain is modelled using a contact interface with a penalty formulation. Figure 7 shows four different states of the ditching sequence (approach, impact, after engine break-off, landing) of the full-aircraft ditching simulation. Contour plots of the vertical displacement in the fluid (left) and of the von Mises stress in the fuselage (right) are presented. The vertical displacement time history of the CoG of the aircraft is provide in addition in Figure 8.

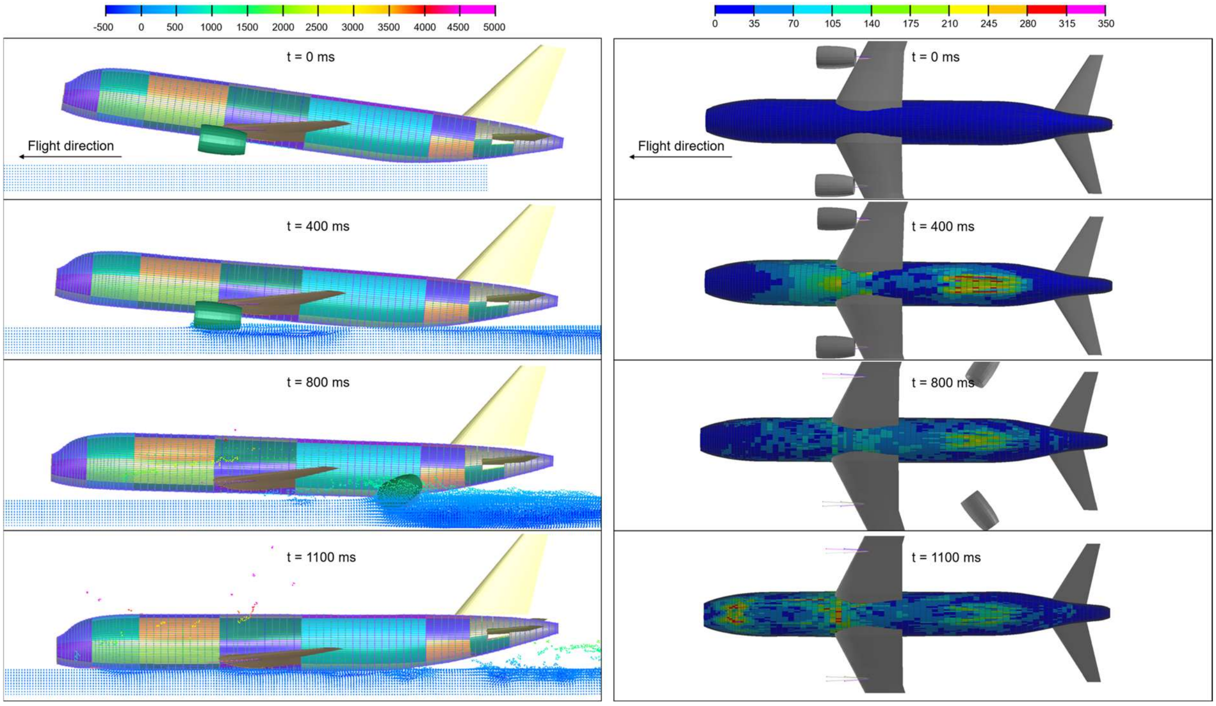

Figure 7. Ditching simulation of the flexible aircraft. Left: contour plot of particle vertical displacements (in mm). Right: contour plot of the von Mises stresses of the bottom fuselage section (in MPa).

The highest hydrodynamic loads can be found at about 400 ms after first contact, when the rear bottom fuselage section is deformed to the maximum by the fluid pressure, causing a deep concave deformation of the skin and reinforcements. The failure criterion of connections is exceeded when the engines enter into the water. Then, the engines separate from the pylons, hit the wing intrados and move away from the aircraft as presented at 800 ms. Later, the front part of the aircraft hits the water surface, also triggered by the nose-down moment caused by the engines impact. At 1100 ms the parts of the fuselage below the cockpit and in front of the wings are subjected to high stresses. This contact causes the aircraft to skip, leaving the front part the water surface (Figure 8) while a second contact of the rear aircraft section was observed. Then the aircraft continues its landing phase up to the end of the simulation at 2000 ms without coming to a complete rest at that moment.

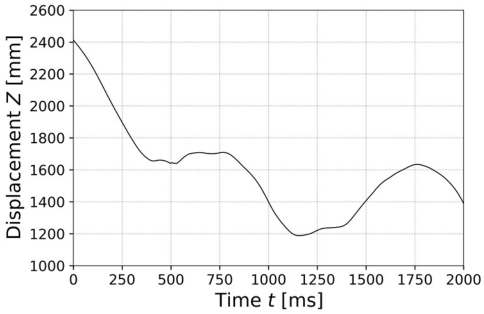

Figure 8. Vertical displacement time history at the CoG position of the aircraft. Initial vertical input at 2.4 m indicates position of the CoG at the begin of the simulation with an initial pitch attitude of 8°.

The elapsed time to complete the simulation was around 21 h, using 8 nodes and a total of 64 processors of a local cluster, and computational features like a multi-model coupling scheme carried out with different suitable time steps for each sub-model. The modelling technique with simpler beam element representations for skin and panel reinforcements proposed in this work is adapted to ditching simulation with flexible aircraft models. The analysis of the global aircraft kinematic behavior and the local structural response can be achieved in a reasonable time. The consideration of mesh sizes according to the flexible panel analysis will be further investigated.

5. Conclusions

In this work, the integration of a modelling technique to represent fuselage skin reinforcements such as stringers and frames by simple beam elements in flexible full-aircraft models was investigated for ditching computations. This approach was enhanced by an analysis of beam-stiffened flexible fuselage panels under guided ditching conditions with computational methods based on the coupled SPH-FE and the ALE-CEL approaches. Results predict good agreement with computations undertaken with shell-stiffened models. Also, the computational effort is significantly reduced. A full-aircraft ditching simulation with beam reinforcements was performed using the SPH-FE method. Results were obtained in a reasonable elapsed time. The global aircraft kinematics as well as the local structural response could be assessed for the impact phase and a significant part of the landing phase of the ditching, demonstrating the interest of integrating beam FE representations for full aircraft ditching simulations.

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